P-25: Subatomic Physics

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Introduction

The Subatomic Physics Group (P-25) is engaged primarily in fundamental nuclear and particle physics research. Our objective is to conduct diverse experiments that probe various aspects of subatomic reactions, providing a more thorough understanding of the basic building blocks that make up our universe. Although our main focus is basic research, there is also a strong and growing effort to turn the group's skills and capabilities to applied programs such as proton radiography. To conduct our research, we often participate in large-scale collaborations involving physicists from universities and institutions around the world, and we participate in and lead experiments at a variety of facilities. Currently, we are conducting research and developing new programs at Los Alamos National Laboratory and other laboratories, including Brookhaven National Laboratory and Fermi National Accelerator Laboratory (Fermilab). The following sections highlight the significant experiments and activities that we are currently pursuing.

Hypernuclei Physics

One of our key interests over the past several years has been the study of lambda (λ)-hypernuclei, where the λ replaces a neutron within nuclei, to explore the strong interaction (the force that holds the nucleus of an atom together). In 1994, we proposed experiment 907 (E907) at Brookhaven's Alternating-Gradient Synchrotron (AGS) to study the feasibility of using the (K^-,π^0) reaction (in which a negative kaon decays to a neutral pion) as a novel tool to produce λ-hypernuclei with energy resolutions significantly better than those produced in the previous (K^-,π^-) and (π^+,K^+) experiments (in which negative kaons decay to negative pions and positive pions decay to positive kaons, respectively). E907 should also be capable of measuring the π^0 weak-decay modes of λ-hypernuclei, which have never been studied before. The LANSCE Neutral Meson Spectrometer (NMS) and associated equipment were moved to the AGS for this experiment. A new data acquisition system and a new array of active target chambers were also successfully installed. Preliminary measurements have provided the first hypernuclear spectrum using the (K^-,π^0) reaction. In addition, the π^0 energy spectrum resulting from the weak-decay of light λ-hypernuclei has also been measured. Data collection has been completed and the data are currently being analyzed.

The PHENIX Program at RHIC

P-25 has also been exploring the subatomic physics that defined the universe at its beginning. Big Bang cosmology pictures a time very early in the evolution of the universe when the density of quarks and gluons was so large that they existed as a plasma, not confined in the hadrons we know today (neutrons, protons, pions, and related particles) (Fig. 1). In 1999, when operations commence at Brookhaven's Relativistic Heavy-Ion Collider (RHIC), it should become possible to create a small sample of such primordial quark-gluon plasma in the laboratory and study its exotic properties. The

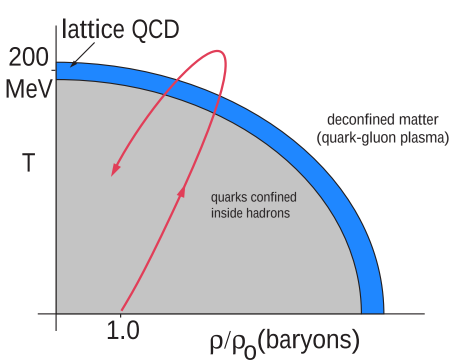

***Fig. 1** Lattice QCD calculations predict that at higher temperatures and densities, there will be a transition of matter from the confined state to the deconfined state, as shown by the solid band. Research with RHIC will explore this transition of matter.*

challenge facing the international collaborators involved in the RHIC program is to find the signatures of the fleeting transition into this deconfined phase of matter. Extending the Physics Division's long history of experiments at the energy frontier, P-25 is playing a major role in defining the physics program for RHIC.

P-25 is also playing a key role in constructing two major subsystems for the PHENIX detector, one of two major collider detectors at the RHIC facility. The PHENIX collaboration currently consists of over 400 physicists and engineers from universities and laboratories in the U.S. and nine foreign countries. Our work focuses on the multiplicity/vertex detector (MVD) and the muon subsystem. The MVD is the smallest and among the most technically advanced of the PHENIX systems. It will be located very close to the region where the two beams of 100-GeV nucleon ions intersect. Its function is to give the precise location of the interaction vertex and to determine the global distribution and intensity of secondary charged-particle production, which is a crucial parameter in fixing the energy density achieved in the collision fireball.

The muon subsystem, the largest of PHENIX's subsystems, consists of two large conical magnets and associated position-sensitive tracking chambers at opposite ends of the detector. Muons are identified by recording their penetration of a series of large steel plates interspersed with detection planes, all of which follow the magnets at each end of the detector. The muon subsystem plays a central role in P-25's physics agenda at RHIC. It is optimized for examining experimental observables at very high temperatures and densities, at which the strong force is smaller and easier to calculate using perturbative quantum chromodynamics (QCD).

RHIC is currently scheduled to begin operations in late 1999, and first results are expected in 2000.

High-Energy Nuclear Physics

Another area of study in P-25 is parton distribution in nucleons and nuclei, and the nuclear modification of QCD processes such as production of J/ψ particles (made up of a pair of charm/anti-charm quarks). We are currently leading a research program centered on this topic at Fermilab. This program (which is discussed further in a research highlight in Chapter 2) began in 1987 with measurements of the Drell-Yan process in fixed-target proton-nucleus collisions (see Fig. 2). These measurements showed that the antiquark sea of the nucleon is largely unchanged in a heavy nucleus. In our most recent measurements during the NuSea Experiment (E866), we also showed that there is a large asymmetry between down and up antiquarks, presumably due to the nucleon's pion cloud (Fig. 3). In addition we showed that the production of heavy vector mesons such as the J/ψ is strongly suppressed in heavy nuclei. We mapped out this effect over a broad range of J/ψ energies and angles. Although the causes of this suppression are not yet fully understood, it is already clear that absorption in the final state

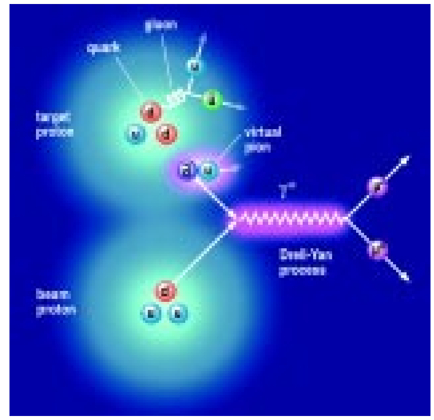

***Fig. 2** A proton consists of three valence quarks held together by gluons in a sea of quark-antiquark pairs. These pairs may be produced by gluon splitting, a symmetric process generating nearly equal numbers of anti-down, $\bar{d}$, and anti-up, $\bar{u}$, quarks, or from virtual-pion production, an asymmetric process that generates an excess of $\bar{d}$. We can determine $\bar{d}/\bar{u}$ by measuring the properties of the muon pairs produced in the Drell-Yan process, which occurs when a quark in a proton beam strikes a sea antiquark in a target.*

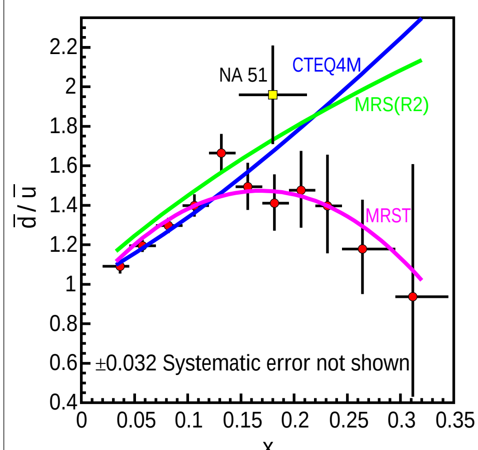

***Fig. 3** The ratio of $\bar{d}$ to $\bar{u}$ in the proton from the FNAL E866 NuSea data as a function of the fraction of the proton's momenta carried by the quark, x. NA51 was the only previous measurement of this quantity. The curves represent various parameterizations of $\bar{d}/\bar{u}$. The curve that best matches that data, labeled "MRST," was proposed only after the FNAL E866 NuSea data were published.*

plays an important role, as do energy-loss of the partons and shadowing of the gluon distributions. Data analysis is nearly complete, and continuing experiments at Fermilab have been proposed.

Liquid Scintillator Neutrino Detector

P-25 also conducts experiments to explore the possibility of neutrino oscillation, which has great implications in our understanding of the composition of the universe. The Liquid Scintillator Neutrino Detector (LSND) experiment at LANSCE has provided evidence for neutrino oscillations, revealing an excess of oscillation events in both the muon-antineutrino to electron-antineutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and muon-neutrino to electron-neutrino ($\nu_\mu \rightarrow \nu_e$) appearance channels. These two channels are independent of each other and together provide strong evidence for neutrino oscillations in the $\Delta\left(m^2\right) > 0.2\ \mathrm{eV}^2$ region. The LSND results, therefore, imply that at least one of the neutrino types in each of these appearance channels has a mass greater than 0.4 eV, a contradiction to standard models that assume neutrinos have no mass. Based on estimates of the number of neutrinos present in the universe, the LSND results suggest that neutrinos contribute more than 1% to the mass density of the universe. The existence of neutrino oscillations has great significance for nuclear and particle physics as well because it means that lepton number is not conserved and that there is mixing among the lepton families, which contradicts the standard models. The LSND experiment, which had its last run in 1998, has also made precision measurements of neutrino-carbon and neutrino-electron scattering, which is of interest for testing the weak interaction.

Booster Neutrino Experiment

As an extension of the work conducted during the LSND experiment, P-25 has been pursuing the Booster Neutrino Experiment (BooNE), which will make a definitive test of the LSND neutrino oscillation results. This experiment will also be conducted at Fermilab. The BooNE detector will consist of a 12-m-diameter sphere filled with 770 tons of mineral oil and covered on the inside by 1,220 phototubes recycled from the LSND experiment (Fig. 4). The detector will be located 500 m away from the neutrino source, which will be fed by Fermilab's 8-GeV proton booster. The proton booster will run nearly continuously, and if the LSND results are indeed due to neutrino oscillations, BooNE will observe approximately 1,000 $\nu_\mu \rightarrow \nu_e$ oscillation events after one year of operation. Furthermore, if oscillations are observed, BooNE will be able to make precision measurements of the oscillation parameters and test for charge-conjugation parity violation in the lepton sector. The BooNE detector should be operational by the end of 2001, and first results are expected a year later.

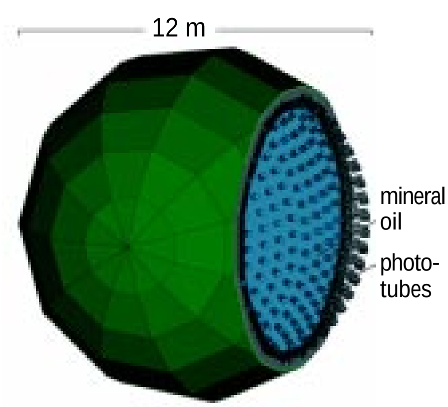

Fig. 4 Conceptual view of the BooNE detector, which will provide a definitive test of the LSND evidence for neutrino oscillations.

MEGA

The apparent conservation of muon number remains a central problem of weak interaction physics, and is thus another area of research in P-25. Experimental evidence to date shows that muons consistently decay into an electron and two neutrons. However, the particle physics community is continually searching for instances that violate muon number conservation, which would give insight into possible extensions of the minimal standard model of weak interactions. MEGA was an experimental program designed to make such a search at the Los Alamos Meson Physics Facility (LAMPF), now known as LANSCE. MEGA, which searched for muon decays yielding an electron and a gamma ray (hence, the acronym), completed its data collection in 1995. The extraction of kinematic properties for all of the muon decay events that potentially meet the MEGA criteria is now complete, and the final sample of about 5,000 events is under careful scrutiny. The combined data from the summers of 1993–1995 are expected to yield a statistical precision that improves the current world sensitivity to this process by a factor of 25 to roughly 3×10^{-12}.

Rho

As part of the MEGA program, the MEGA positron spectrometer was used to measure the Michel parameter ρ (rho), which governs the shape of the polarization-independent part of the energy spectrum for positrons emitted in normal muon decay. The standard model predicts ρ to be 0.75; based on experimental results to date, it is known to be within 0.3% agreement with that value. Deviations from 0.75 might indicate the need for right-handed currents in the standard model. In our experiment, the energy spectrum for over 2×10^8 positrons was recorded and data were taken under several conditions to help with the analysis of systematic errors. Despite these precautions, we anticipate that energy-dependent systematic errors will limit the accuracy of the result to a level that is currently being evaluated. Analysis of the data is scheduled for completion in 1999.

Electric Dipole Moment of the Neutron

P-25 is also participating with the Neutron Science and Technology Group (P-23) in a Laboratory project aimed at improving the limit on the electric dipole moment (EDM) of the neutron. Our interest in this topic is driven by the recent observation of violation of time reversal invariance in the neutral kaon (K^0) system. Many theories have been developed to explain this time-reversal-invariance violation, but most have been ruled out because they predict a sizable EDM for the neutron, which experiments have yet to verify. Today, new classes of highly popular models, such as supersymmetry, predict EDM values that are potentially within the reach of experiment. In addition, if the observed baryon-antibaryon constitution of the universe is due to time-reversal-violating symmetry breaking at the electroweak scale, the range of predicted EDM values is also measurable. We are currently working towards experimentally verifying the feasibility of conducting an experiment that should improve the limit on the neutron EDM by two orders of magnitude to 4×10^{-28} e*cm.

Fundamental Symmetry Measurements with Trapped Atoms

With the advent of optical and magnetic traps for neutral atoms, a new generation of fundamental symmetry experiments has arisen that exploit point-like, massless samples of essentially fully polarized nuclei. In P-25, we are pursuing a measurement of the beta-spin correlation function in the beta decay of ^{82}Rb confined to a time orbiting potential (TOP) magnetic trap as a means to probe the origin of parity violation in the weak interaction (see the research highlight on this topic in Chapter 2). We also envision a new generation of atomic-parity nonconservation experiments that test the neutral current part of the weak interaction. In the latter experiments, measurements of the beta-spin correlation function with a series of radioactive isotopes of cesium and/or francium could eliminate atomic structure uncertainties that presently limit the ultimate precision of beta-spin correlation function measurements. This should improve the quality of our results.

Ultracold Neutrons

P-25 is also participating with P-23 in experiments to provide better sources of UCN, which can be trapped to study neutron properties. Solid deuterium converters have been proposed as a source of UCN for some time. Recently, experiments conducted in the Physics Division have made it clear that coupling a solid deuterium moderator to the high cold-neutron densities available from a pulsed spallation neutron source, such as the Los Alamos Proton Storage Ring, may provide a UCN source with several orders of magnitude higher neutron density than reactor driven sources such as the Institute Laue-Langevin source.

Theory

In addition to the fundamental research conducted in our group, P-25 has a strong theory component, which consists of a staff member and a number of short- and medium-term visitors from universities and laboratories throughout the world. Theoretical research focuses on basic issues of strong, electromagnetic, and weak interactions topics that complement the present activity of the experimental program and that impact possible future scientific directions in the group. As such, our theoretical component facilitates interaction between experimental and theoretical activities in the nuclear and particle physics community and contributes to a balanced scientific atmosphere within the group. Recent theoretical activity has focused on neutrino interactions and masses, parity violation in chaotic nuclei, deep inelastic scattering, hadron properties in free-space and in nuclei, and QCD at finite temperatures.

Proton Radiography

Although our main focus is basic research, P-25 also has several applied programs, such as proton radiography. There are two goals for the proton radiography program. The first is to demonstrate that high-energy proton radiography is a suitable technology for meeting the goals established for the advanced radiography program; the second is to develop the capability of 800-MeV proton radiography for meeting immediate programmatic needs. These goals are highly coupled since many of the techniques developed for 800-MeV radiography can be used at higher energies. Most of our effort in the last year was focused on the 800-MeV program because funding restrictions limited progress in our planned 25-GeV demonstration at Brookhaven's AGS. We are currently exploring the possibility of building a 50-GeV machine, the proton radiography interim-step machine (PRISM) that will be dedicated to proton radiography experiments (Fig. 5). For more information on our proton radiography efforts, refer to the research highlight on this topic in Chapter 2.

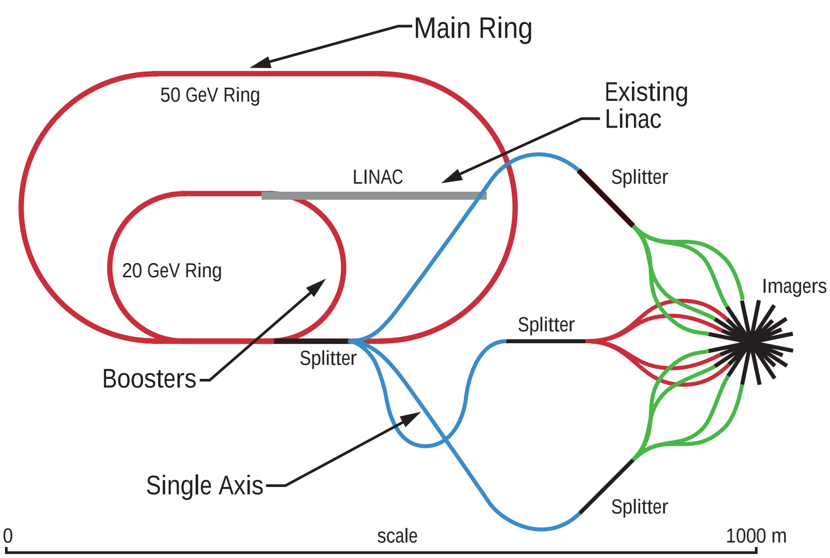

***Fig. 5** Concept of the proton radiography Advanced Hydrotest Facility (AHF). PRISM, a subset of the AHF, would include the linac injector, the main 50-GeV acceleration ring, a single-axis extracted beam line, a firing point, and a lens system.*

Quantum Computation using Cold, Trapped Ions

In another applied program, P-25 is collaborating with P-23 to develop quantum computation technology. Quantum computation is a new computational paradigm that is much more powerful than classical computation because it allows computing with quantum-mechanical superpositions of many numbers at once. In a quantum computer, binary numbers will be represented by quantum-mechanical states ("qubits"). We are developing a quantum-computational device in which the qubits will be two electronic states of calcium ions that have been cooled with a laser to rest in an ion trap. Once these ions are resting in the trap, we will perform quantum logical operations with a laser beam that is resonant with the qubit transition frequency and is directed at individual ions. We have recently succeeded in trapping and imaging a cloud of calcium ions using two titanium-sapphire lasers, one frequency-doubled to 397 nm, the other to 866 nm. Future experiments will focus on increasing the number of ions that are simultaneously trapped, which will move us closer to realizing a functioning quantum computation system.

Carbon Management and Mineral Sequestration of CO_2

P-25 is also focussing on ways to solve global environmental issues, such as the overabundance of carbon dioxide (CO_2) in the atmosphere. Today, fossil fuels account for 80–85% of total world energy use. The reasons for this include their abundant supply, high energy-density, public acceptance, ease of use and storage, existing infrastructure, and, most importantly, their low cost. The only threat to their continued widespread use is the possible environmental consequence of the vast amounts of CO_2 released into the atmosphere as a result of their combustion. The use of fossil energy has raised the level of CO_2 in the atmosphere by roughly 30% since their earliest use, and emissions could reach 10 times current levels in the next 50 years as populations grow and the standard of living improves worldwide. Thus, mitigation of these CO_2 emissions is becoming an important global issue. P-25 is participating in a Laboratory-wide program to apply scientific expertise to the CO_2 issue. Our proposed solution to this problem is to react CO_2 with common mineral silicates, which exist in quantities that far exceed the world's coal reserves, to form carbonates like magnesite or calcite. These reactions are exothermic and thermodynamically favored under ambient conditions. Thus, this disposal option can easily address the CO_2 problem in a safe and permanent manner that also promises to be relatively inexpensive. We are currently participating in experiments with other Laboratory divisions to demonstrate the soundness of this proposal.

Education and Outreach

P-25 group members continue to be active in education and outreach activities, both as participants in programs sponsored by the Laboratory and as individual citizens who volunteer their time for various activities. Recent group member activities include acting as judges for the New Mexico Supercomputing Challenge, serving as consultants for the Teacher Opportunities to Promote Science (TOPS) program, participating in career days and college days at New Mexico schools, and visiting local classrooms. We also coordinated, organized, and participated in the Teacher's Day at the annual meeting of the American Physical Society's Division of

Nuclear Physics.

In addition to these outreach activities, P-25 sponsors several high school, undergraduate, and graduate students to work on projects within the group. Through their individual schools, these students study computing, engineering, and electromechanical technical support, as well as physics, and they supplement their learning through interaction with Laboratory mentors and real on-site experience. Several students are writing theses based on the work they do at P-25.

Further Information

All of the research described is aimed at increasing our understanding of subatomic reactions, and we are poised to make exciting discoveries in nuclear and particle physics over the next several years. To learn more about these projects, as well as the other work being conducted in our group, please see the project descriptions in Chapter 3. Some of our major achievements are also covered as research highlights in Chapter 2. These include our work in high-energy nuclear physics and proton radiography.